Solar Greenhouse Heating

Final Report

McGill University

BREE 495 - Engineering Design 3

Group 2

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Executive Summary

The Macdonald Campus Horticultural Centre begins seeding in late-February to provide fresh fruit and produce to students, staff, and community members, as well as to offer educational tours and sustained research opportunities throughout the summer and fall semester. An electrically-heated long tunnel greenhouse is currently used for seeding and germination prior to planting. However, as temperatures in February and March are quite variable, seeded trays are often transported to the indoor centre and back to the greenhouse when temperatures become more favourable. As the current system is both time and energy intensive, an alternative was needed to extend the greenhouse growing season by providing an effective, safe, sustainable, cost-efficient, and accessible solution; a solar thermal heating system was designed. The system consists of two automated fluid circuits. The first circuit operates throughout the day by absorbing heat from a liquid-finned solar thermal heat exchanger and transferring it to a water-glycol fluid, which is then pumped to a hot-water tank inside the greenhouse. The second circuit is initiated when soil temperatures reach below 10°C. An electric heating element is used in the hot water tank when the heat exchanger cannot provide enough heat. The heated water then circulates from the tank to tubing under the greenhouse tables, heating the seedbed soil through free convection. Through rigorous testing and simulations the system was optimized, it was determined to be economically advantageous compared to the current system, and risks as well as safety concerns were mitigated and addressed. Moving forward, the system will be fully installed and operational for the 2018 seeding season.

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1. Introduction

The McGill Macdonald Campus Horticultural Center is a produce farm located in Ste-Anne-de-Bellevue, Quebec. It provides numerous student internships, educational tours, research opportunities as well as fresh produce to the local community. The horticultural center is an important institution in the community, for social, economic and environmental reasons. A common practice by the horticultural center is to seed plants in late february, then transplant them outside when it is sufficiently warm. A major concern for this system is the variable temperature in late february which often prohibits early seeding in the greenhouse. Nightly temperatures in the greenhouse often drop drastically below 0°C, to the point that seedlings may not germinate. Current methods using electric heating fans to keep the greenhouse and plants warm, are inadequate. It is this project's goal to provide a sufficient heating system to the horticultural center by implementing a novel solar heating design. The greenhouse is 5.5 m wide, 2.8 m tall and 29.3 m long (Image 1), of which only a single 11.5 m by 2.4 m table of seedlings will be heated (Image 2).

Image 1. Horticultural Centre Seeding Greenhouse Image 2. Seeding table

The current heating system is both high cost, due to high electricity usage, and labour intensive. The greenhouse currently operates two heating ceiling fans and two floor fans. The fans heat the whole greenhouse and are therefore much more energy intensive than necessary, making them very inefficient. Energy is being wasted heating the entire greenhouse, when only the seedbeds need to be warm. The heaters work all night, or until they are turned off, therefore heating the plants even when the temperature is naturally high enough. This system also presents inconveniences, as seedlings may have to be moved indoors when the temperature gets too low. Personnel often have to come in late in the evening to bring the plants indoors, or switch on the fans for especially cold nights. The project was done with the consultation of Michael Bleho chief technician at the Horticultural center, Vijaya Raghavan as mentor (McGill) and advice from Lyle Lemon of Solcan™.

2. Potential Solutions

Initially five solutions were considered: commercial electric heaters, electric propagators, thermal mass storage heating, furnace heating and solar thermal heating. These ideas were considered based on current industrial uses, resources available, and the environment of the greenhouse.

2.1 Electric Heaters

Four commercial electric heaters are currently used. The bottom two heaters are Stelpro PCH4800T (Stelpro) and the top two heaters are Ouellet OAS02036 (Ouellet) and Caloritech GE5A5G. These heaters would need to be upscaled dramatically to meet the heating needs of the greenhouse, due to the fact that a significant amount of generated heat is wasted by space heating. Approximately 17 heaters, at a cost of $200 each (Stelpro), would have been needed to maintain a constant temperature of 10°C. The maintenance cost would be high as well, with $2379.45 a year for electricity billing. This was calculated from the consumption of 17 heater of 1440 kWh each for 10 hour nights for a month, using a rate of $0.0971/kWh (Hydro-Quebec). Safety is also a concern as the fans can short circuit and possibly shock greenhouse users.

2.2 Propagation Trays

Another electric solution was to use small heating trays called seed propagators. These trays are similar to regular seeding trays, but with the addition of covers which can hold heat and moisture. The heat is propagated through the trays by low watt heat filaments, which pass under the trays heating the seedbeds directly. Compared to the electric fans this would use much less electricity, approximately 10 W/tray. Each tray covers 76 cm by 18.5 cm with a cost of $50.00 per unit. For this system, 700 trays would be needed to cover the whole greenhouse. This would be an initial investment of $35 000. Similar to trays are heating mats, they heat similarly to the trays (Armbruster,1966). They can be up to 1.2 m by 0.508 m, and only 187 of them would be needed. The total energy demand would be 19.4kW and with each unit costing $90.00. Again, this would be a costly solution, with an initial investment of $16 380.

2.3 Thermal Mass Storage

A passive method was also considered, using a thermal mass storage system. This method uses a material with high specific heat as a heat sink, absorbing heat in the greenhouse during the hot day and releasing it slowly to the plants during the night. It is common practice to use barrels of water (Smith, 2000) or concrete walls for this purpose. For a greenhouse, water barrels are generally more appropriate. This simple system would have barrels placed in the north side of the greenhouse, so as not to block solar radiation. During winter, they would have to be drained so that the water inside does not freeze and break the barrels. The primary constraint with this system is the large gradient of temperature from one end of the greenhouse

to the other. The side close to the barrels may be warm enough but the furthest part may not be. Space limitations prohibit more liberal barrel placement. This method is risky as there are no possible safety precautions in case the system does not sufficiently heat the seedlings.

2.4 Furnace Heating

Furnace heating was another option. The horticultural center has access to large amounts of biomass, which results in an inexpensive fuel source. The biomass fuel can be wood, dried plant materials, corn stocks, or various other discarded biological material. The important part of choosing a feedstock is based on availability and quality. Some feedstock will burn longer, release more heat and have various ash contents (Keoleian *et al.,* 2007). This will allow for less refueling and more efficient heating. Pelletization is also another method to increase efficiency as it increasing the density, therefore increasing the burning duration (OAFR). Other added benefits to the furnace is that it can add CO_2 to the greenhouse which can be beneficial to the plants (Royal Society Of Chemistry). The biochar produced from the burning of the fuel can also be used as a soil amendment which has been shown to increase the water use efficiencies and yield (Lehmannn *et al.*, 2003). However, this system is costly and has a high potential for burn hazards. The initial investment would be between $1000 - $5000 for a furnace (US Stove). The operational requirements would involve refueling and cleaning the ash produced. As well, it has to be fed throughout the night, therefore it is high on labour. The furnace is also a fire hazard, increasing risk and needed mitigation.

2.5 Solar Thermal Heating

Solar thermal heating was the final design solution. This system is similar to bulk heating, in that a fluid is heated by the sun and used to store heat energy. In this case, solar heat will be collected by a solar heat absorber into a fluid, the fluid will then be stored in an insulated tank and finally this fluid will be distributed through pipes in order to heat the greenhouse (NRC, 2014). Two types of solar systems exist, direct and indirect systems. Direct systems involve the heating of water and then the storage of that heated water. An indirect method, uses a fluid for heating and then transfers the energy to a separate fluid through a heat exchanger. The second system is used in colder climates where the fluid outside has a chance of freezing. In such case antifreeze is used in the external section. The horticultural center is in possession of two Solcan™ 3001 Liquid Finned Tube Collector. The efficiency of the collectors can reach close to 80% (Solcan, 1982).

After much consideration of the benefits and constraints associated with each system, the solar thermal system was chosen as the ideal solution. This will be further elaborated in the following section with regards to the specified criteria of the client.

3. Design Parameters

Through discussions with the client, the Macdonald Horticultural Center, as well as the McGill Sustainability Projects Fund, a set of design parameters for our system were created. The solution must be safe, environmentally sustainable, effective, cost-efficient, and easy to use.

3.1 Safety

Safety was a high design priority. The greenhouse is a moist environment, so electrical equipment must be properly contained to prevent shorting, and should be at an adequate distance from the seed trays so equipment does not need to be moved during watering. The solar thermal system achieves this as the only electronics used are the pumps, pump controllers, and hot water tank heater. Both the pumps and hot water tank were designed to be used with water. The electronic switches and their arduino boards controlling them will be placed well away from the seed beds.

3.2 Environmental Sustainability

Furthermore, the design is environmentally sustainable, notably when compared to the current system. The bulk of the energy input to the system is done through solar energy, drastically reducing the energy cost. The only energy required to run the system is to circulate the fluids through the use of pumps. There is an electrical backup heating coil in the storage tank, however this is only a backup to ensure the seeds do not get too cold, and is not expected to be required often.

3.3 Effectiveness

The calculations for effectiveness of the system will be discussed later in this paper, however a lower boundary was set for soil temperature required. This lower temperature is 10^0C. The boundary is based on the lower boundary of the prefered range of temperature for onion seed germination (AAF 2010), as onions are the main crop grown in the greenhouse at the time of year in which the system would be active. Germination can still occur as at temperature as low as 2^0C, but using the lower boundary of prefered temperature both gives better germination rates, and provides a buffer zone for the system.

3.4 Cost-Efficiency

In order to be funded by the McGill Sustainability Projects Fund in a reasonable time frame, the system must cost less than $5500. As the solar panels for the system were provided for no cost by the Horticultural Center, the final cost is relatively low. Originally, the design also incorporated a storage tank that was also provided by the Horticultural Center. The tank was later found to be inadequate, based on poor insulation and small storage volume. Despite this, the system still comes within the budget provided by the Projects Fund. The main costs are a

storage tank purchased from Solcan™, and glycol solution to prevent freezing of pipes during early operation. Other materials can be obtained at low cost from local hardware stores.

3.5 Accessibility

One of the main concerns from the Horticultural Center was that their current practice of seeding indoors then transporting the seedlings outdoors when the weather improves, is labour intensive. Watering is difficult indoors, and at times the overnight temperature drops below what the seedlings can handle, and must be moved back inside. Once installed, the designed system will be mostly automatic, with the exception of the beginning and ending of the growing season. At the beginning of the season, the solar panels must be uncovered and the water tanks filled. At the end of the season, the water must be drained and the solar panels recovered. The water must be drained to prevent freezing during the winter, and solar panels covered to prevent degradation of the glycol solution due to high temperatures during the summer. During regular operations, the pumps are controlled automatically, and the only maintenance required is removing any snow built up on the solar panels.

4. System Overview

The complete system will use both an exterior and interior circuit to collect and distribute heat to the plants respectively (figure 1). The exterior circuit will gather heat through the solar heat exchanger during daylight hours and the internal circuit will distribute this heat to the plants during nights. Each circuit will have a pump, and the pumps will be operated with a digital switch through an arduino control. The control will be monitored with LM-35 temperature sensors. An insulated water storage tank will act as an intermediary between the circuits, storing the thermal energy during the day for nightly use.

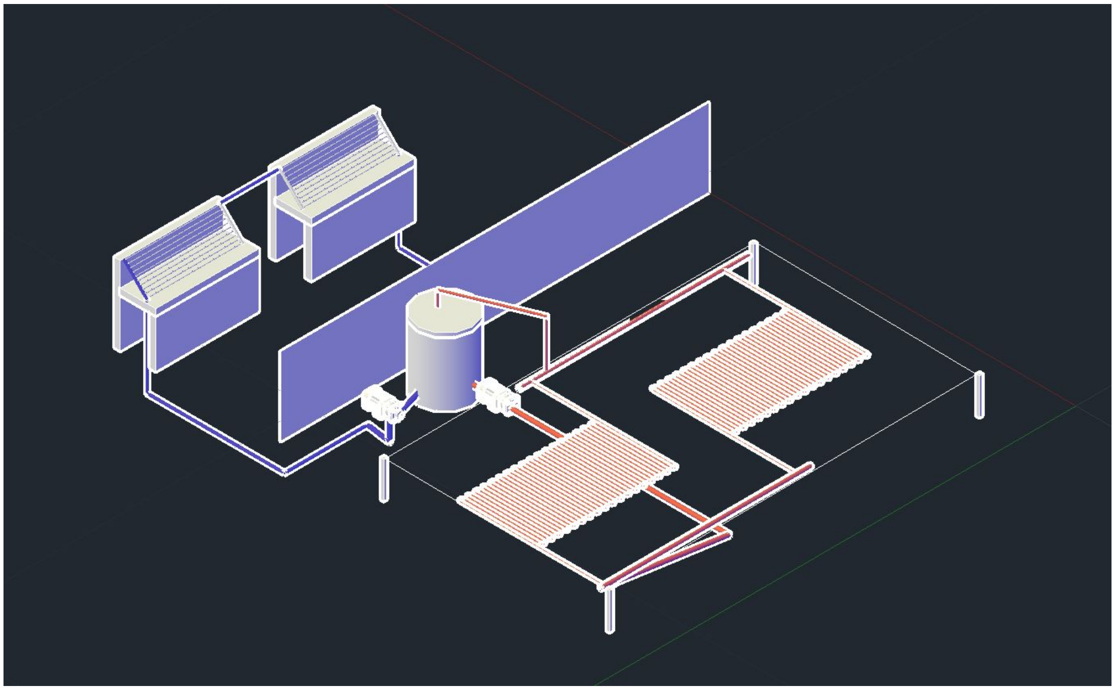

Figure 1: Complete system. External loop in blue, internal loop in red

4.1 Exterior Circuit

For the external circuit, temperature sensors will be placed in both the solar heat exchangers as well as the storage tank. The temperature differential will be monitored, and the pump will only be activated when the panels reach a temperature 5 ℃ hotter than the tank temperature. This is to ensure that the heat exchangers do not act to cool the tank. As well, this sensor will be able to restrict the circuit from acquiring too much heat. Should the heat in the tank exceed a threshold value, the circuit can be switched off. While preliminary results show that this may not be necessary as the PVC piping material can withstand temperatures of over 100 ℃, should the water begin to approach boiling temperatures, the pressure within the pipes would exceed advised values. From initial testing the temperature within the panels has never reached over 80 ℃, even during optimal day conditions. However, the temperature threshold value will be set as a safety precaution to ensure temperatures never rise above 80℃.

4.2 Internal Circuit

For the internal circuit, the sensor will monitor the air temperature surrounding the plants and activate the pump, and circuit, when temperatures drop below 20 ℃. This ensures efficiency in heating as the temperature during most days is sufficient for the plants, without additional heating. The hot fluid can better preserve heat energy when it remains in the insulated tank and only operates when necessary. As well, should the heat in the tank not be adequate, a thermometer is installed with a backup heating coil that will provide additional heat to the fluid and ensure the plants are adequately heated.

4.3 Hot Water Tank

The tank specifications are 300 L (80 gal) volume with an internal heat exchanger coil (figure 2). Originally the tank design operated both circuits under a single fluid and thus did not require an internal heating coil. However this design proved to be inefficient and costly due to glycol anti-freeze concerns. Using a singular fluid would require a propylene glycol mixture of the entire fluid base (330L of 50/50 glycol mixture), which would both raise the initial cost, (roughly $1700), as well as the operating cost as the glycol degrades quickly and would require replacement every few years. Having an internal heat exchanging coil within the tank allows for a two fluid system, with a glycol mixture only necessary for the external loop (20L of 50/50 glycol mixture). The internal circuit could use water as a working fluid and the heating filament and thermometer in the tank would ensure that the water never drops below a threshold temperature of 20 ℃.

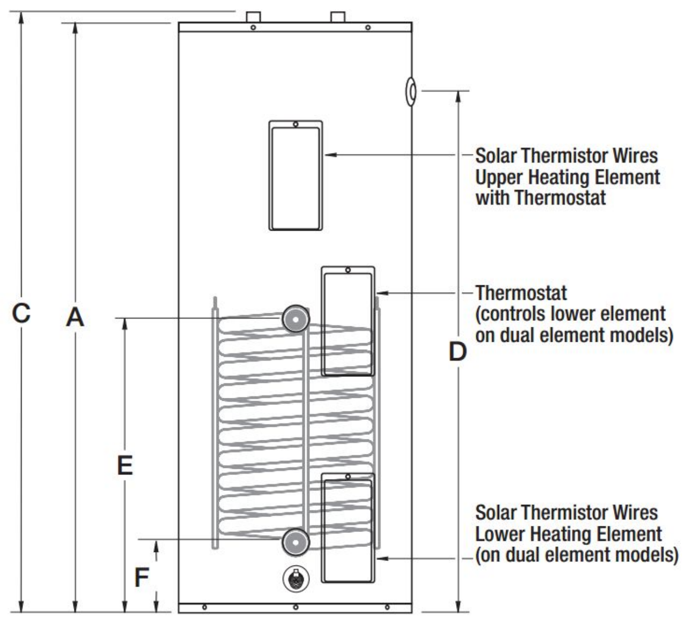

Figure 2. Side view of the Bradford White™ 80 gallon tank which used for the system heat storage (Bradford White). The tank contains an internal heat exchanging coil as well as a backup heating filament.

4.4 Pumps

To circulate the fluids throughout the separate circuits, two pumps are needed. To match with commerical measurements of piping head used for available pumps, english units will be used. Equivalent bend length was calculated using 3.6 feet per 90° and 180° bend. Pressure loss constants were found using Hunter Friction Loss Tables (Hunter Industries).

Table 1: Calculation of Total Pumping Height

Indoor Circuit						
Flow rate (gmp)	psi Loss / 100 ft	Actual Pumping Height (ft)	Bend Equivalent Length (ft)	Length of Pipe (ft)	psi Loss	Total Pumping Height (ft)
1.0	0.5	9.0	291.6	518.4	4.0	18.1
2.0	1.8	9.0	291.6	518.4	14.3	41.8
Outdoor Circuit						
Flow rate (gmp)	psi Loss / 100 ft	Actual Pumping Height (ft)	Bend Equivalent Length (ft)	Length of Pipe (ft)	psi Loss	Total Pumping Height (ft)
1.0	0.8	7.5	46.8	41.2	0.3	7.8
2.0	2.9	7.5	46.8	41.2	1.2	8.7

As suggested by Solcan^{TM}, pumps from Wilo Star will be used. Specifically Wilo Star S 21 (3) and S 16 (3) circulation pumps. As can be seen in figure 3 below, the S 21 can overcome an 18 ft head at low flow rates, which are required for the indoor circuit, and the S 16 can produce high flow rates at a pumping height of 8 ft, which is necessary for the outdoor loop.

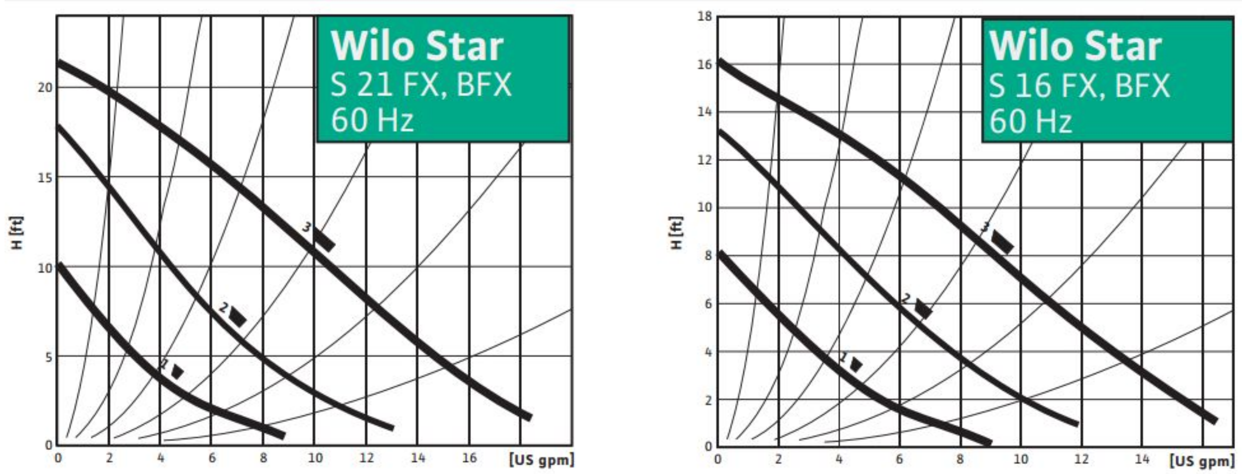

Figure 3: Head (ft) vs Flow rate (US gpm) for Wilo Star S 21 & 16 circulation pumps (Wilo Star Canada)

5. Prototyping and Testing

To verify the effectiveness of the system, several simulations were conducted. The simulations were intended to provide information to determine key materials needed for the system as well as to provide an estimation on the system's functionality.

5.5 Exterior Circuit

The initial tests were conducted on the external greenhouse circuit to verify that the system could gather enough heat energy during the day. To simulate the outside scenario, the outdoor pipes and heat exchangers were constructed in CAD modelling software and then used in heat transfer simulations in Ansys™. The pipe designs were estimated to be 4 m in length, neglecting bends. The pipes were analysed as Polyvinyl Chloride (PVC) and assumed to have a surface temperature of 0 ℃, corresponding to average ground temperatures at a depth of 1 foot in early spring.

To model for the heat exchanger, practical tests were conducted with stagnant water on a sunny day to estimate surface heat flux. The heat exchanger was filled with 2.5 L of water and left in a position of 45° vertical slant facing southward at 11:00 am. The fluid temperature was monitored to raise 51.5 ℃ in 35 minutes, resulting in a heat flux of 240.14 W/m^2. This surface heat flux was then applied to the copper pipes in the heat exchanger model, and the system was simulated under fluid flow conditions (figure 4). The inlet temperature was specified to be 60 ℃, the maximum temperature the physical thermometer would allow. This maximum temperature would result in the highest heat losses, as it has the largest temperature differential with the environment, and would give worse case heat loss estimates.

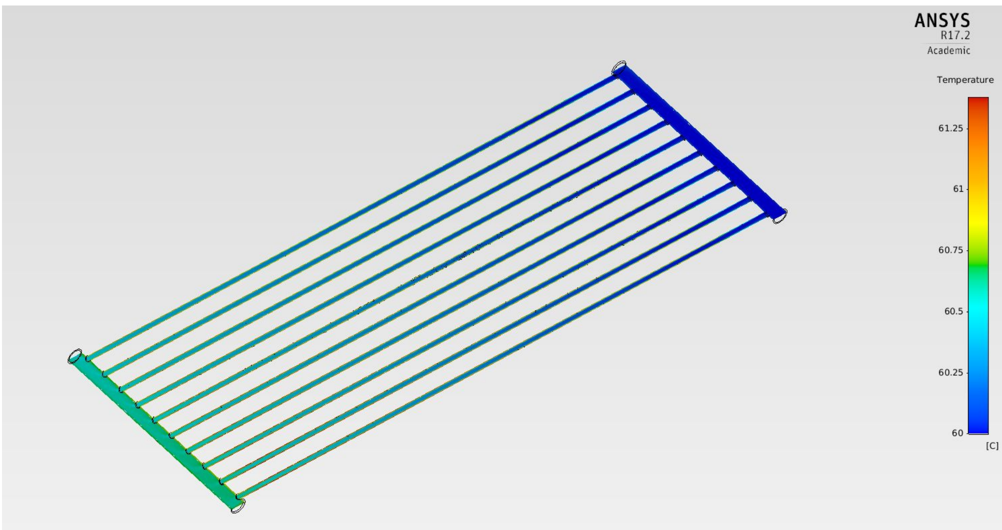

Figure 4: Heat gain through the solar heat exchanger under inlet conditions of 60℃ and a flow rate of 0.908 kg/s

The full exterior system was tested for heat gains and heat losses for various flow rates under maximum loss conditions. These tests served two purposes: to ensure heat gains were larger than heat losses during day operations, and to verify the appropriate flow rate to maximize heat gains.

The flow rates used for this simulation were 0.182 kg/s to 0.908 kg/s (corresponding to 1 m/s to 5 m/s average flow velocity for 3.175 cm (1.25in) piping, and the estimated minimum and maximum for the specified pump). The corresponding heat losses and gains are displayed in table 2. It was determined that the maximum ratio of heat gain occurs at more rapid speeds of flow rate. This is a result of heat losses being reduced by a large degree through rapid rates of underground piping. Therefore the maximum pumping speed should be attempted for the external circuit

Table 2. Heat measures for variable flow rates in external circuit.

Flow Rate	Pipe Heat Loss	Solar Heat Gain	Heat Gain Ratio
0.182 kg/s	0.006 ℃	0.566 ℃	94
0.908 kg/s	0.001 ℃	0.105 ℃	105

Under the conditions of 0.908 kg/s flow rate, the average temperature gain would be 0.560 ℃ per full pass. With a full circuit length of 46.8 m, the 300 L tank of fluid would heat at a rate of roughly 40 ℃/hr. This would be an adequate heat gain to prepare our tank fluid for night operation inside the greenhouse.

5.2 Interior Circuit

The secondary tests were conducted on the internal loop to determine its heat output and heat loss through night operations. Components of the system were constructed through a CAD model and appropriated into Ansys^{TM} software to simulate heat flows throughout the night. The model was run through various flow rates between 0.5 kg/s and 1.5 kg/s (corresponding to average velocities of 1 m/s to 3 m/s for a 1.27 cm (0.5in) diameter tube) to determine the effect of flow rate on heat loss. The flow rates were determined as the recommended minimum and maximum rates for the specific pump chosen. The results demonstrated heat loss ranging from 1.55 ℃/hr to 3.06 ℃/hr, for the slow and fast flow rates respectively, assuming initial heat storage of 300 L of 60 ℃ water (figure 5). This concludes that a slower rate of flow will result in greater energy conversion throughout the night. Available materials, PEX (cross linked polyethylene) and nylon 6 were also tested but results showed negligible difference. The most suitable material was then determined to be nylon due to price and availability.

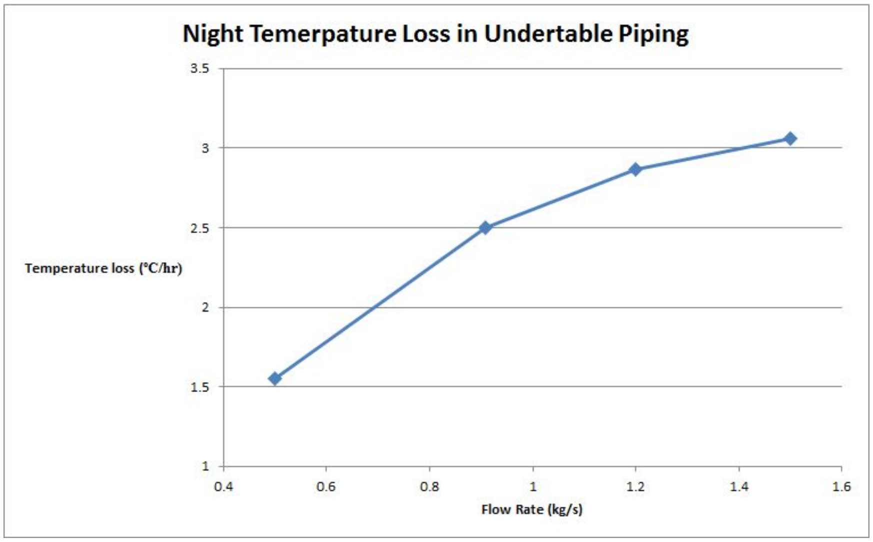

Figure 5. Heat losses at varying flow rates for the entire 300L of water. Simulations were run for over 200 iterations to ensure convergence of less than 10^{-7} residual.

The flow rate of 0.5 kg/s was tested to verify sufficient heat output to the plant trays. For this simulation, a volume of air was generated around the piping and determined to have equal surface convective heat loss as the piping ($8.16W/m^2$ as determined by methods in Fand, Morris, & Lum, (1977)). This assumption neglects the vital natural convective heat transfer directly around the tubing. However this is necessary, as a more accurate model requires the simulation of the large greenhouse structure, which is too extensive for the available version of the Ansys™ program. The assumption can be made more accurate in consideration of the thermal blankets used by the horticultural centre. Thermal blankets are suspended roughly one foot above the plants to trap hot air around the plants to prevent heat loss through convection. Under these conditions, the models can be used to accurately estimate heating conditions for the plants.

The heating distributed to the pants should also be sufficient for the entire night duration. With an initial fluid temperature of 60 ℃ and a rate loss of 3.06 ℃/hr (maximum estimated loss), the fluid temperature would remain at approximately 30 ℃/hr after 10 hours of use. Even at this lower input temperature, heating is still sufficient for the plants. As shown in figure 6, with a fluid input temperature of 30 ℃ , the heating would still be sufficient for seedlings (>10 ℃). This verifies that should the tank adequately store heat during the day of 60 ℃, the system will be able to provide heat for the duration of the night.

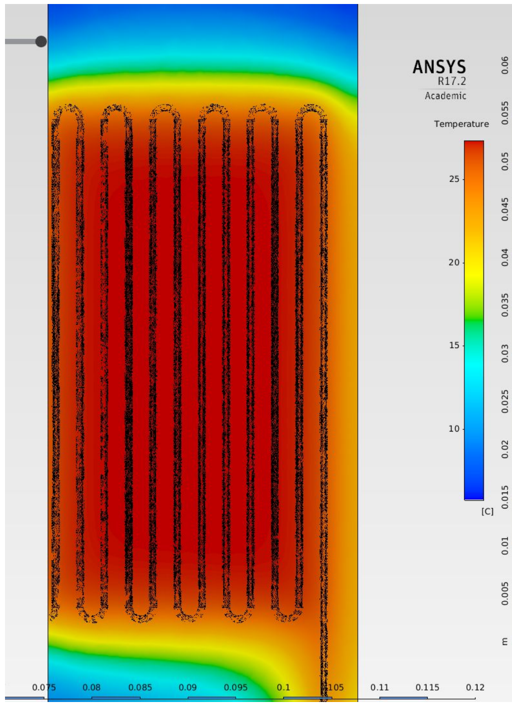

Figure 6. Air temperature 10 cm above the under table piping

The spacing between passes was also determined to be 20 cm. As can be seen from figure 6, this spacing allows for near constant temperature between tubes, allowing for equal heating to plants. If a larger spacing was using the temperature between passes and directly above a tube would differ to a degree where trays may need to be shifted to ensure all plants receive near equal heating. Shorter spacing between passes would increase the cost of tubing materials.

6. Final Design Specifications

The final system design will use a nylon 6 tubing for under table piping, with diameters of 1.27 cm (0.5in). The system will have two parallel flows to reduce the heat differential between inlet to outlet (figure 7a). The spacing between passes will be 20 cm and have a total of 37 passes for each section (figure 7b).

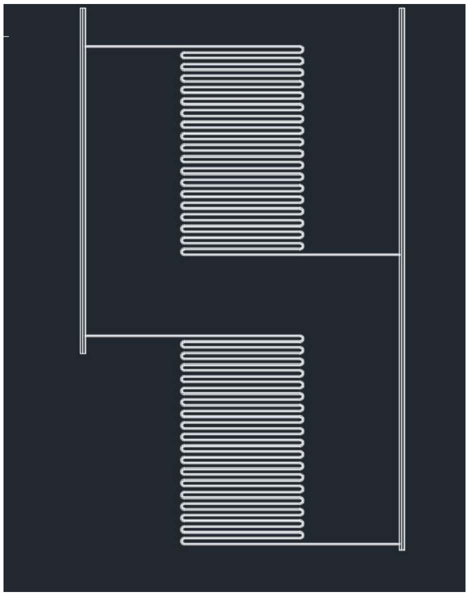

Figure 7a. Undertable piping.

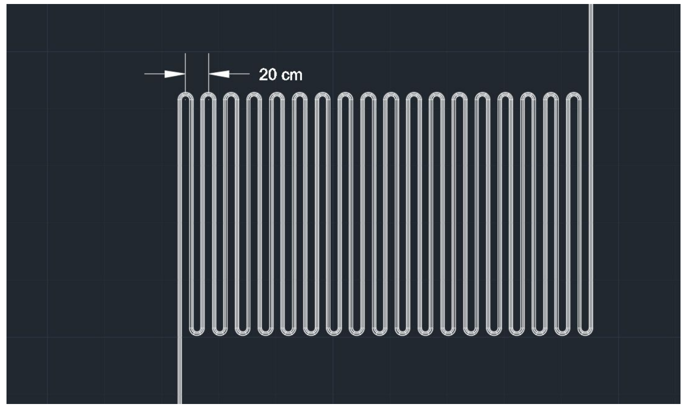

Figure 7b. Spacing between undertable piping

The pump model used for this circuit will be a Wilo Star S 21 (3). Pumping for this circuit will be at a rate of 0.5 kg/s or as slow as the pump allows. This will decrease our nightly heat losses. The system will operate between thresholds of 80 ℃ to 20 ℃, but under normal conditions is expected to stay between 60 ℃ and 30 ℃. This will allow for sufficient heating of the plants with only occasional necessity for the use of the electric filament backup heating.

The external circuit will use approximately 10 m of PVC piping and will operate between the same temperature thresholds. The pipes will be of 3.175 cm (1.25in) diameter and will contain approximately 20 L of 50/50 propylene glycol mixture solution. This circuit will require a separate pump, a Wilo Star S 16 (3), and will be running at a flow rate of 0.908 kg/s, or as fast as the pump will allow.

Both system will utilize LM-35 temperature sensors through an arduino micro computer. The arduino will be encased in a waterproof box constructed of steam treated wood to prevent water damage. The wires connecting the circuits will be encased in a thick protective polymer coating as well to prevent water corrosion.

The solar panels will be placed on a frames and positioned southward on a tilt of roughly 60°. The azimuth for March in Montreal varies between 92.3° (at sunrise, 6:15) and 269.7° (18:00), with the maximum altitude of 44° (National Research Council Canada). For this reason placing the panels at an angle slightly greater than 45° will allow for maximum solar radiation. The panels will be placed on a steam treated wooden frame (figure 8a), with a base 1.4 m above the ground (figure 8b). This height was determined through observation of the minimum height required to receive light on the north side of the greenhouse for 90% of the day in March.

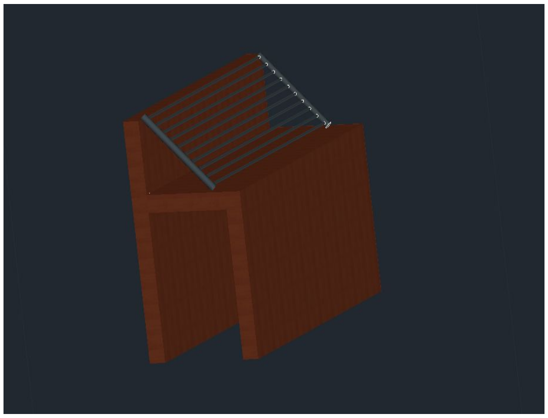

Figure 8a. Wooden frame from an isometric view. Solar heat exchanger is drawn without external casing to show inner piping layout

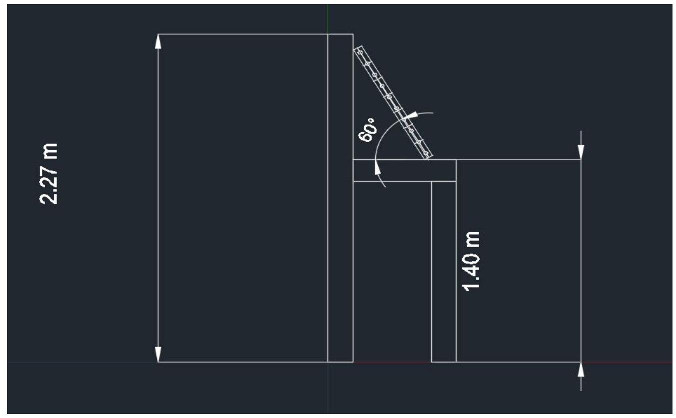

Figure 8b. Side view of wooden frame, used to demonstrate dimensions

7. Risk Analysis and Safety Considerations

A qualitative risk assessment was performed using guidelines from the US department of energy for energy-related project management (DOE, 2013), and altered according to the specific scenario related to the proposed project. Table 3 displays the risk assessment rankings, and table 4 offers a risk assessment matrix along with mitigation measures and considerations.

Table 3: Risk Assessment Rankings

		Probability		
		1 - Low	**2 - Medium**	**3 - High**
	1 - Low	**1**	**2**	**3**
	2 - Medium	**2**	**4**	**6**
Severity	**3 - High**	**3**	**6**	**9**

Table 4: Risk Assessment Matrix

Risk Area				
Safety	**Technology**	**Schedule**	**Labour**	**Cost**
Risk Description [(Probability, Severity) Score]				
Contamination from leaks in under-table piping (1, 2) 2		Timeline Delayed (3, 1) 3	Labour not available (1, 1) 1	
- Soil Contamination from underground piping (2, 2) 4	- 10 degrees not met (1, 2) 2	- Coordination of workshops (1, 2) 2	Unskilled Labour (1,2) 2	
- Burns from Overheating (1, 3) 3	- Material Failure (1, 3) 3			Cost of project more than anticipated (2,3) 6
Considerations / Mitigation				
- Automated temperature controls - Water used in under-table piping - Diluted Glycol mixture in underground piping	- Installed back-up heating - Thorough material tests and simulation - Pressure valves and gauges installed	- Sufficient time before system needs to be implemented - Workshops coordinated in advance	- Low maintenance system - Labour readily available through client - Operation and safety courses given to all users	- Source back-up funding

8. Economics

To best determine whether or not the project is profitable a cost-benefit analysis was performed while comparing the proposed project to the current system. As large components, such as the water tank and the pumps, have a lifespan of ten years, the cost-benefit analysis was calculated for a ten-year duration. Criteria for the analysis include a payback period of less than five years (determined through consultation with the client), a net present value greater than 0, and an internal rate of return greater than the cost of capital, estimated at 10%. Costs of the project include materials (new and replacement), maintenance, construction labour, and back-up heating, while benefits of the project are energy savings compared to the current system, labour savings, and crop loss reductions. A thorough breakdown of the aforementioned costs and benefits is as follows.

8.1 Costs

- Materials

Table 5: Material Costs and Lifespans

Materials	Price	Lifespan (years)
Nylon Tubing	$765	25
Pumps (2) Total price:	$777	10
Glycol	$194	5
Hot Water Tank (Solcan™)	$2,200	10
ABS piping	$144	25
Fittings	$50	20
Wires and LM35 Temp sensor	$15	10
Arduino	$40	5
Digital Switch (2)	$60	10
Frame (most likely metal)	$600	10
Panels	$0	20
Total	$4,845	

For a ten year cycle, ending at the beginning of the tenth year, material replacements at year 5 include glycol and the arduino.

- Construction Labour

Calculated for 35 hours of work at $13.75/hour plus additional benefits through the AMUSE union for student workers, totalling $500 for construction labour.

- Maintenance Labour

A very low maintenance system with an estimated total of 5 hours of work per year to cover the panels and do necessary adjustments, totalling $70/year. Year 5 involves 10 hours of work to drain and replace the glycol, as well as cover the system, and any adjustments, totalling $140.

- Back-up Heating

Back-up heating costs were calculated on a worst-case-scenario (WCS), where the system would be running for 15 hours a night for 90 nights during the year. Using the formula $q = mc_p\Delta T$, where;

m = Tank Volume x Density of Water = 75 gallons x 1000 kg/m^3 = 0.283906 m^3 x 1000 kg/m^3 = 283.906 kg

C_p = 4185.5 J/kg*K

ΔT = 3.06, maximum heat loss per hour (WCS) (refer to section 5.2 for calculations)

Table 6: Back-up Heating Calculations

q=	3636163.00	J/hr
	1.01	kW
MAX hrs/night		
15.00	15.15	kWh/night
nights/year		
90.00	1363.56	kWh/year
Rate G $/kWh		
0.10	132.40	$/year

Table 7: Cost totals over ten-year cycle

Costs	**year 0**	**years 1-4, 6-10**	**year 5**
Materials	4845		240
Construction	500		
Maintenance		70	140
Back-up Heating (WCS)		132.40	132.40

8.2 Benefits

- Energy Saving

Energy savings were calculated based on what the current system uses, through the operation of 4 4.8kW electric heaters.

Table 8: Energy Saving Calculations

Max hrs/night		
10	192	kWh/night
nights/year		
80	15360	kWh/year
Rate G $/kWh		
0.0971	1491.456	$/year

- Labour Saving

The current system is also not labour-intensive, involving just 0.5 hours a day during the two week primary seeding period to transport trays from the horticultural centre to the greenhouse. At $13.75/hour, the total labour costs of the current system is $96.25/year.

- Crop Loss Reduction

Through consultation with the client, it was estimated that 2% of onions per tray are lost due to inconsistent heating and transport stress.

Table 9: Crop Loss Reduction Calculations

Number of Trays	Onions/Tray	Losses/Tray (%)	Onions loss/ Tray	Total Onion Loss
175	225	2	4.5	787.5

Onions are sold for $0.75, therefore a loss of 787.5 onions results in a crop loss of $590.63

Table 10: Benefit totals over ten-year cycle

Benefits	**year 0**	**year 1-10**
Energy Saving	0	1491.46
Labour Saving	0	96.25
Loss Reduction	0	590.63

8.3 Cost-Benefit Analysis

The cost-benefit analysis is tabulated in table 10, where net present value is calculated as the sum of present values, with a cost of capital of 10%.

$$NPV = \frac{B_0 - C_0}{(1+i)^0} + \frac{B_1 - C_1}{(1+i)^1} + \ldots + \frac{B_T - C_T}{(1+i)^T}$$

Table 11: Cost-Benefit Analysis Results

Year	0	1	2	3	4	5	6	7	8	9	10
Benefits	0.00	2178.33	2178.33	2178.33	2178.33	2178.33	2178.33	2178.33	2178.33	2178.33	2178.33
Costs	5345.00	202.40	202.40	202.40	202.40	512.40	202.40	202.40	202.40	202.40	202.40
B-C	-5345.00	1975.93	1975.93	1975.93	1975.93	1665.93	1975.93	1975.93	1975.93	1975.93	1975.93
PV	-5345.00	1796.30	1633.00	1484.54	1349.59	1034.41	1115.36	1013.96	921.79	837.99	761.81
NPV	-5345.00	-3548.70	-1915.70	-431.16	918.43	1952.84	3068.20	4082.17	5003.95	5841.94	6603.74

As calculated in table 11, the net present value for a ten year cycle is greater than 0, the discount period is less than five years, and the internal rate of return is greater than the cost of capital.

Net Present Value = $6603.74 (> 0)

Discounted Payback Period = 3.47 years (< 5 years)

Internal Rate of Return = 22% (> 10%)

Therefore, as all of the criteria are met, the project is in fact profitable and economically advantageous compared to the current system.

9. Conclusion

To extend the growing season at the Macdonald Campus Horticultural Centre, an improved greenhouse heating system is required. The proposed detailed solution is a solar thermal heating system that will absorb heat from a liquid-finned solar collector during the day and store it in a hot-water tank where it will then be pumped during the night through radiative under table piping. To ensure the effectiveness of the design, an internal heating coil is installed in the tank to offer back-up heating. As well as effectiveness, the remaining criteria include safety, environmental sustainability, cost-effectiveness, and accessibility, which are all met through the proposed design. Safety is ensured through careful considerations of possible risks, and associated mitigation strategies. Environmental sustainability is achieved through the use of renewable solar energy, as well as a reduction of energy-grid use compared to the current electrical system. Cost-effectiveness is demonstrated through the cost-benefit analysis, where it is determined that the proposed design is economically advantageous compared to the current system. Lastly, accessibility and ease-of-use is highlighted through the automation of the system, as well as the low-maintenance design.

Moving forward, the system will be installed in the coming weeks, and safety/operation courses will be offered to all users at the beginning of May. Educational tours to highlight the benefits and the novel technology of the system will be given to various groups throughout the summer by the client.

Future improvements to the design could include efficiency and effectiveness improvements to allow the system to run year-round, offering further opportunities for the Horticultural Centre. Furthermore, it would be in the best interest of the client if future funding could be secured to continue the use of the system after the ten-year lifecycle of certain components, such as the pumps and the water tank.

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11. References

Alberta Agriculture and Forestry (AAF) (2000). Soil Temperature for Germination. Alberta Agriculture and Forestry
http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex1203

Armbruster, F. (1966). Electric Heating mat. U. P. Office. United States. US3535494A.

Bradford White. Ecostor™ Sc Solar Indirect System Single Coil Electric Backup Models (Closed Loop, Single-wall). www.bradfordwhite.com Web. Accessed: 2017-04-09

Department of Energy. 2013. Project Management Plan Examples: Project Risk Assessment. Available at www.energy.gov/sites/prod/files/2013/05/f0/PM_PLAN_EXAMPLES_54-56.pdf

Fand, R. M., Morris, E. W., & Lum, M. (1977). Natural convection heat transfer from horizontal cylinders to air, water and silicone oils for rayleigh numbers between 3 × 102 and 2 × 107. International Journal of Heat and Mass Transfer, 20(11), 1173-1184. doi:http://dx.doi.org/10.1016/0017-9310(77)90126-0

Hunter Industries. Friction Loss Tables. www.hunterindustries.com. Web. Accessed: 2017-03-20

Hydro-Quebec. Rates and Billing [Online]. Hydro Quebec. Available: www.hydroquebec.com [Accessed 2016-11-06 2016].

Keoleian, A. T., & Volk, A. T. (January 18, 2007). Renewable Energy from Willow Biomass Crops: Life Cycle Energy, Environmental and Economic Performance. Critical Reviews in Plant Science, 24, 385-406

Lehmann, J., Silva J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B. (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant and Soil 249: 343–357, 2003.

National Research Council Canada. Sunrise/sunset calculator. *Natural Resources Canada. Government of Canada.* www.nrc-cnrc.gc.ca. Web. Accessed: 2017-04-02

Ontario Ministry of Agriculture, Food and Rural Affairs (January 04, 2016). Biomass Burn Characteristics. http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm

Ouellet. Commercial Industrial Suspended Unit Heater [Online]. Ouellet. Available: www.ouellet.com [Accessed 2016-11-09 2016].

Smith, S. (2000). Greenhouse Gardener's Companion, Revised: Growing Food & Flowers in Your Greenhouse or Sunspace. Fulcrum

Solcan. Solcan 3001 Liquid Finned Tube Collector [PDF]. Solcan. 1982. 37, 1-6.

Solcan. Solar Thermal. London, ON. Available at http://solcan.ca/solar-hot-water/

Stelpro. Portable Heater (PCH4800T) [Online]. Stelpro Available: http://www.stelpro.com/en-CA/portable-heater [Accessed 2016-11-06 2016].

US Stove. 2500 Square Foot Hotblast Wood Furnace with Twin 550 CFM Blowers [Online]. Available: www.wayfair.ca [Accessed 2016-11-09 2016].